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RESEARCH ARTICLE

Green-Cane Harvested Sugarcane Crop Residue Decomposition as a Function of Temperature, Soil Moisture, and Particle Size

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Abstract Sugarcane, a complex hybrid of *Saccharum* species, is grown on over 170,000 ha in the state of Louisiana. In 2016, the crop was worth $750 million US. Green-cane harvest, widely used in sugarcane producing countries, deposits up to 20 Mg ha^{-1} of crop residue annually. Green cane harvesting of sugarcane is recognized to be a more sustainable management opportunity than burning residue, or standing or heaped stalks. In Louisiana, cool, wet winters coupled with the crop residue left on the field reduce ratoon yields by as much as 10% year^{-1}. However, the residue represents an important opportunity to improve degraded, low organic matter soils to facilitate sustainable sugarcane production. Our objective was to evaluate how temperature, soil moisture, and particle size influence sugarcane residue decomposition rates. In laboratory experiments, we observed rapid residue carbon (C) mineralization rates at temperatures of $\geq$ 23 °C across all soil moisture levels tested, and calculated the residue decomposed by 71–95% over the course of the 155 days experiment. Particle size also increased decomposition, with 61, 72, and 91% decomposition observed for the $>$ 2.0, 0.25–2.0, and $<$ 0.25 mm particle size fractions, respectively. The results indicate that earlier cut cane fields have the best chance to decompose green-cane harvested residue by taking advantage of warmer October temperatures, and that shredding the residue further increases its susceptibility to microbial decomposition. Future experiments will study field decomposition of residue in situ as well as incorporation of residue C into soil organic matter.

Keywords Crop residue decomposition · Soil carbon · Green-cane harvest · Sustainable sugarcane

Introduction

Sugarcane, a complex hybrid of *Saccharum* species, is grown on over 170,000 ha in the state of Louisiana. In 2016, the crop was worth $750 million, and contributed over $2 billion in economic impact (American Sugar Cane League of the USA, Inc. 2017). Most growers now harvest sugarcane green, using the chopper harvester combine to simultaneously cut and chop stalks into 0.30- to 0.45-m-long billets, while removing extraneous leaf and top material using the combine's extractor fans. Green-cane harvesting of sugarcane is recognized to be a more sustainable management opportunity than burning standing or heaped stalks. Benefits of retaining and recycling the crop residue layer include increased soil carbon (C) and mineral nutrients, decreased soil erosion and runoff, protection of ratoons from freezing, and soil moisture conservation (Nunez and Spaans 2008; Sandhu et al. 2013). For Louisiana, the crop residue input represents the largest organic addition to soils with relatively low levels of C typically encountered in areas under continuous sugarcane cultivation. Disadvantages of retaining sugarcane crop residue include ratoon sugar yield loss (Viator et al. 2009), allelopathy (Webber et al. 2017), high carbon/nitrogen (C:N) ratio, cooler soil emergence temperatures (Sandhu et al. 2013), and limited weed control effectiveness (Judice et al. 2007; Richard and Dalley 2006). The delay in soil

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drying and warming can have a large impact on crop yield performance in temperate climates. Low early spring temperatures, combined with large amounts of surface crop residues, delayed soil warming in no-till corn plots and lowered yields by up to 25% in some years (Vyn and Raimbault 1993). A similar process is occurring in Louisiana sugarcane fields.

Green-cane harvest deposits 4–8 Mg ha^{-1} of dry sugarcane trash or residue on the soil surface annually in Louisiana (Johnson et al. 2007). In Australia, dry matter estimates are 14–19 (Spain and Hodgen 1994) and 7–12 Mg ha^{-1} (Robertson and Thorburn 2007) and in Brazil, 10–20 Mg ha^{-1} (Galdos et al. 2010). The amount of sugarcane crop residue returned to fields is substantial, when compared to other row crops, including small grain cereals, 2–4 Mg ha^{-1}, (Steiner et al. 1999); corn, (*Zea mays* L.), 1.4–7.0 Mg ha^{-1} (Buyanovsky and Wagner 1986; Humberto Blanco-Canqui and Lal 2014; Karlen et al. 2014); wheat (*Triticale aestevium*), 5.6–6.2 Mg ha^{-1} and soybean (*Glycine max*), 0.4–0.6 Mg ha^{-1} (Buyanovsky and Wagner 1986). Sugarcane crop residue consists of green and senesced leaves, immature internodes, and mature stalk pieces that are not collected by the harvester (Viator et al. 2006). Eggleston et al. (2009) reported that over one-third of the total dry biomass from sugarcane is from leafy material, particularly from green leaves. Crop residue mass is larger for the plant-cane crop, when compared to the ratoon crops. Sandhu et al. (2013) reported post-harvest residue levels for plant cane, first ratoon, and second ratoon of 13–23, 8–17, and 12–14 Mg ha^{-1}, respectively. In Brazil, post-harvest leaves and tops contributed 11.5 Mg dry matter ha^{-1} year^{-1} and 5.1 Mg C ha^{-1} year^{-1}, respectively, when compared to rhizomes and roots that contributed 4.6 Mg dry matter and 1.5 Mg C ha^{-1} year^{-1} (Carvalho et al. 2017).

The additional input of crop residue could translate into increases in soil organic carbon (SOC) as the residue is decomposed. Soil C was sequestered at a rate of 0.70–2.04 Mg ha^{-1} year^{-1} for the top 0.3 m depth for coarse- and fine-textured soils, respectively, after converting from a burnt to an unburnt sugarcane harvesting system in Brazil (Cerri et al. 2011). In South Africa, the SOC concentration was 50 g C kg^{-1} in plots where crop residue was not burned for 40 year, as compared to 41–43 g C kg^{-1} for burned plots. In fertilized, non-burned plots, the SOC concentration was actually higher than in uncultivated, native grassland (47 g C kg^{-1}) (Graham et al. 2002). However, in more temperate areas, the residue exhibits a mulching effect, resulting in cooler soil temperatures as a result of increased soil moisture. The effect is not dissimilar to certain no-till agricultural systems that exhibit a crop growth lag in the early spring as a result of higher soil moisture contents and concomitant lower soil temperatures (Fabrizzi et al. 2005). For example, subsequent sugarcane yields were reduced by 3.3 Mg cane ha^{-1} and 610 kg sugar ha^{-1} when crop residue was retained, and by 6.7 Mg cane ha^{-1} and 1050 kg sugar ha^{-1} when residue was burned after ratoon dormancy ended (Viator et al. 2009). Incorporating soil cultural practices that would improve decomposition rates could reduce the spring mulching effect while taking advantage of the benefits of increased soil organic matter (SOM) and recycling of plant available nutrients. Therefore, the objective of these experiments was to evaluate crop residue decomposition rates at different temperatures, soil moisture, and particle size typically encountered in a temperate sugarcane production system.

Materials and Methods

Experiment-I

Cancienne silty clay loam soil (fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquepts) and post-harvest crop residue were collected from the USDA-ARS Sugarcane Research Unit Ardoyne Farm in Schriever, LA (Latitude 29°38′11″N, Longitude 90°50′25″W). Alluvial processes segregate soils into coarse-textured (e.g., silt loams) and fine-textured (e.g., clays) soils often within the same field. For example, the USDA farm is located on the south side of Bull Run Road in Schriever, LA, formerly Chacahoula bayou, and the elevation drops from 2.1 to 0.6 m above sea level from the road to the swamp. The predominant soils transition from Cancienne silt loam to Schriever clay (very fine, smectitic, hyperthermic, Chromic Epiaquerts) over a distance of only 500–840 m.

The soil was collected from the 0–20 cm depth of a field with a long history of continuous sugarcane production, sieved to pass 2-mm screen, and stored at room temperature (22–25 °C) in the dark. The gravimetric soil moisture was 0.13 g H_2O g soil^{-1}. Soil pH of a 1:1 soil/water slurry was measured using an electrode. Soil organic C and total nitrogen (N) were analyzed using dry combustion on a Flash 1112 elemental analyzer (ThermoFisher Scientific). Mehlich III extractable potassium (K), phosphorous (P), calcium (Ca), sulfur (S), magnesium (Mg), sodium (Na), boron (B), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and aluminum (Al) were analyzed by inductively coupled plasma spectroscopy (ICPS). Soil ammonium and nitrate were extracted with 1 M potassium chloride and analyzed by cadmium reduction. The total soil cation exchange capacity was calculated by summing Mehlich III extractable cations. Sugarcane crop residue was collected from the soil surface immediately after green-cane harvest of sugarcane in 2015, dried at 65 °C, ground with a Wiley

Mill No. 4 (Thomas Scientific, Swedesboro, NJ) to pass a 1-mm screen, and stored at room temperature. A nitric acid-digested sample was analyzed for N, P, K, Ca, Mg, S, Fe, B, Mn, Cu, Zn, and Al by ICPS. Soil and crop residue chemical characteristics are presented in Table 1.

Fifty g of dry weight equivalent soil was placed into 125-mL Erlenmeyer flasks. Either 5.0 or 7.5 g distilled water was added to the soil in one-third of the flasks to elevate the soil moisture to 0.23 and 0.28 g H_2O g $soil^{-1}$, respectively. The final third samples remained at 0.13 g H_2O g $soil^{-1}$. One half of the flasks were amended with 0.25 g of dried sugarcane crop residue (0.5% by weight). The residue was mixed thoroughly with the soil using a spatula. Observed soil moisture measurements ($n > 6550$) in a field near where the soil was collected (< 100 m) ranged from 0.15 to 0.50 g H_2O g^{-1} soil from September 2016 through February 2017, which roughly corresponds to the Louisiana sugarcane harvest and dormancy interval when crop residue could be on the soil surface. The highest incubation soil moisture level (0.28 g H_2O g $soil^{-1}$) is less than the mean for the field (0.32 g H_2O g $soil^{-1}$), but additional water added to the flasks resulted in saturated soil conditions preventing satisfactory mixing of crop residue. The flasks were placed in 1 L canning jars that contained 25 mL of distilled water in the base of the jar. All flasks were sealed in the jars with screw lids containing a rubber septa. The jars were divided into 3 groups with each group being incubated at either low (11 ± 0.95 °C), ambient (25 ± 1.1 °C), or high (33 ± 2.7 °C) temperature for the duration of the experiment. The temperatures were chosen to represent typical field conditions at different times of the year. During 2013–2016, temperatures of 11 and 25 °C were observed in the months of November–March, and April–October, respectively. The high temperature allowed temperature quotients (Q_{10} values) to be evaluated (De Neve et al. 1996).

Headspace carbon dioxide (CO_2) accumulated was measured 10 times over 155 days from each jar, which was vented after each measurement to replenish oxygen levels. At each sample time, jars were mixed with a 50-mL syringe a few minutes prior to drawing a 0.5-mL sample with a 1.0-mL syringe that was injected onto a 2 m Porapak Q 80/100 mesh packed column fitted to a Shimadzu GC-8A gas chromatograph with a thermal conductivity detector (TCD) (Mikha et al. 2005). The amount of CO_2 analyzed in the injection was calculated by comparing the TCD response (μV) for an unknown injection with a standard injection of a 0.01 mol CO_2 mol^{-1} gas standard. The standard injection was made numerous times during each analysis of all 72 jars. The amount of CO_2 analyzed was converted to a $gram^{-1}$ soil basis by multiplying by 840 (volume inside the jar not occupied by soil, water, or flask) and dividing by 50 g dry weight soil.

Experiment-II

Cancienne silty clay loam soil (fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquepts) and crop residue used in Experiment-I was used in Experiment-II. However, the crop residue was ground first through a Jeffco mill (Bisbane, Queensland, AUS) to a size of 2–4 mm. The material that passed a 2-mm sieve was ground with a Wiley Mill No. 4 (Thomas Scientific, Swedesboro, NJ) to pass a 0.250-mm screen. Thus, three particle sizes were established: > 2.0, 0.25–2.0, and < 0.25 mm. A sample of each size was analyzed as described previously (Table 1). Particle size was altered to evaluate a current cultural practice that growers use, where the newly deposited crop residue is shredded to a finer size using a rotary cutting mower. Grower observations indicate that the finer crop residue decomposes quicker than the coarser residue. The experimental protocol was similar to the Experiment-I. The initial soil sample contained 0.17 g H_2O g^{-1} soil, which was altered on half of the samples to 0.23 g H_2O g^{-1} soil. The flasks were amended with 0.25 g of the > 2.0, 0.25–2.0, or < 0.25 mm dried sugarcane crop residue (0.5% by weight). The flasks were placed in 1-L canning jars and incubated at 10 ± 0.95 °C. Headspace CO_2 accumulated was measured 13 times over 139 days. The single temperature was chosen for Experiment-II because the shredding practice is used in the cooler harvest

Table 1 Soil chemical properties of Cancienne silty clay loam used for the incubation experiments

Total C (g kg^{-1})	Total N (g kg^{-1})	pH 1:1	Exch. capacity ($cmol_c$ kg^{-1})	Mehlich III extractable (mg kg^{-1})										
				P	K	Ca	Mg	Na	B	Fe	Mn	Cu	Zn	Al
10.1	0.9	5.5	15.1	11	71	1390	271	40	0.40	276	57	2.3	1.6	439
1 M KCl extract (mg kg^{-1})			Nitric acid digest elemental composition (mg kg^{-1})											
NH_4-N	NO_3-N													
3.4	6.6		180	740	2120	2150	108	15	9560	325	8.2	38	5400	

months of November–January. Carbon mineralization was measured as described for Experiment-I.

Data Analysis

Experiment-I included 3 soil moisture levels (0.13, 0.23, and 0.28 g H_2O g^{-1} soil), 3 incubation temperatures (11, 23, and 32 °C), 2 crop residue rates (0 and 0.25% by weight), and 4 replications for a total of 72 experimental units. Experiment-II included 2 soil moisture levels, 4 crop residue treatments, and 4 replications for a total of 32 experimental units. Crop residue chemical properties were compared across incubation experiments using ANOVA. Otherwise experiments were analyzed separately. Estimates of crop residue decomposition were calculated using first-order kinetics by plotting the natural log of the percent remaining at each time point, for each treatment subtracted from the no-residue control, using the regression tool in Excel (Microsoft, Redmond, CA). Total C mineralization was calculated by summing the individual time point CO_2 carbon (CO_2-C) observed. The rate of C mineralization was estimated by dividing the accumulated headspace C by the number of days between sample time points. For statistical comparisons, soil moisture, temperature, crop residue, and residue chemical properties were set as fixed variables and replication was set as a random variable as necessary for testing. The ANOVA used the mixed procedure in SAS version 9.0 (SAS Institute, Cary, NC). Means of significant effects were separated using the PDIFF option with the SAXTON macro at the $P = 0.05$ level (Saxton, 1998).

Results and Discussion

Soil and Crop Residue Characterization

The soil pH (5.5) was lower than the usual observed at the Ardoyne Farm site, when compared to previous reported measurements taken at the same location 6.0–7.1. However, the role of carbonates in soil C cycling should be minimal and isolated to small mollusk shells frequently encountered in the area (> 2 cm in diameter). The level of soil C (10.1 g kg^{-1}) is typical for a silty clay loam soil under continuous sugarcane cultivation and is equivalent to a SOM level of 17.4 g kg^{-1}. The sugarcane fields are generally tilled on the row sides and wheel furrows at least three times per year in the spring and early summer, and completely plowed and tilled prior to starting a new cane cycle and to terminate a cane cycle every 4–5 years. Conventional tillage increases SOM decomposition by releasing physically protected particulate organic matter (POM) through the destruction of C-rich macroaggregates (Six et al. 2000). Exposing coarse and fine POM to the indigenous soil microbial population often leads to increased soil C and N mineralization (Mikha and Rice 2004). A survey of south Louisiana soils found that continuous sugarcane cultivation resulted in a 45% reduction in SOM quantified by loss-on-ignition, when compared to adjacent land not previously used for agricultural production, with values of 28.2 and 51.6 g kg^{-1}, respectively (White 2011). The total soil C:N:P ratio was 150:11.4:1.0 (molar) and the soil C:N ratio was 13.1 (molar). The C:N:P ratio is lower than published values found in natural ecosystems including grasslands and forests, 186:13:1 (Cleveland and Liptzin 2007). This could be a further indication of degraded SOM, in which P is behind as C and N were removed from the soil by burning, mineralization, denitrification, leaching, or as crop biomass. Or, a higher P concentration may indicate soil P is enriched due to mineral fertilizer additions, P is conserved by arbuscular mycorrhizal fungi–plant root associations (Wilson et al. 2009), or P is translocated to rhizomes as a component of non-structural carbohydrate reserves (Owensby et al. 1977).

The soil cation exchange capacity (15.1 $cmol_c$ kg^{-1}) was similar to previously reported values (16 $cmol_c$ kg^{-1}) as well as unpublished yearly soil test results at the Ardoyne Farm. The low CEC of coarser soils correlates to a reduced capacity to store organic C through clay mineral interactions, including occlusion in soil microaggregates (Six et al. 2000). The low CEC may also be an artifact of low SOC, as OC constitutes a significant proportion of CEC in coarse-textured soils. The low levels contrast with finer-textured soils (e.g., Schriever clay, 36 $cmol_c$ kg^{-1} soil) often < 1 km apart, underscoring the importance of SOM-contributions to the soil's exchange capacity, especially for coarser-textured soils. The inorganic N levels were not expected due to the time lapse from the last fertilizer applied (April, 2015) to the soil collection time (August, 2016). But, given the soil C:N ratio is 13:1, the NH_4-N and NO_3-N should increase the initial stages of residue decomposition (Lueken et al. 1962).

Separating the crop residue by particle size provided important information regarding C and N dynamics that would not be observed using a single particle size (Table 2). But the average total C and N of > 2.0, 0.25–2.0, and < 0.25 mm was numerically similar to the < 0.1 mm fraction. Total C was significantly lower in the < 0.25 mm size fraction, when compared to the > 2.0, < 1.0, or 0.25–2.0 mm size fractions, which were similar (Table 2). The C:N ratio decreased as particle size decreased, and ranged from 75 to 159, reflecting the low mineral N content of sugarcane extraneous leaf material as reported previously (White et al. 2017). The fine fraction (< 0.25 mm) exhibited the greatest mineral content, when compared to the coarse (> 2.0 mm) and

Table 2 Sugarcane crop residue elemental composition for each particle size

Particle size (mm)	Total C (g kg^{-1})	Total N (g kg^{-1})	C:N ratio	Nitric acid digest (mg kg^{-1})											Mineral content (g kg^{-1})	Recovery[b] (g kg^{-1})
				P	K	S	Ca	Mg	B	Fe	Mn	Cu	Zn	Al		
< 1.0	396	4.2	95	3	24	7	46	14	8	2910	187	6	26	3440	10.8	901
> 2.0	485	3.1	159	2	40	4	20	6	3	379	57	5	14	428	4.01	983
0.25–2.0	421	5.2	81	2	28	6	37	10	7	983	108	5	25	1110	7.52	923
< 0.25	233	3.1	75	3	28	4	33	20	9	6220	209	7	62	6810	16.5	744
$P \leq 0.05$[a]	x	ns	x	ns	x	ns	x	x	x	x	x	ns	x	x		
< 1.0	a		b		b		a	b	ab	b	a		b	b		
> 2.0	a		a		a		c	d	c	d	c		c	c		
0.25–2.0	a		b		b		ab	c	b	c	b		b	c		
< 0.25	b		b		b		b	a	a	a	a		a	a		

[a]An 'x' or an 'ns' indicate whether the ANOVA results indicate significant differences in elemental means at the $P < 0.05$ level. Letters in a column indicate if the particle size elemental means are statistically similar at the $P < 0.05$ level according to the SAXTON macro option

[b]The calculated recovery of organic and inorganic elements. Oxygen and hydrogen contents were obtained from Hassuani et al. (2005)

medium (0.25–2.0 mm) fractions, with values of 16.5, 4.01, and 7.52 g kg$^{-1,}$ respectively; the < 1.0 mm size fraction used in Experiment-I was representative of the three fractions, with an average mineral content of 10.8 g kg^{-1}. The fine fraction contained significantly higher levels of Mg, Fe, Mn, Zn, and Al, when compared to the coarse and mid-fraction, and the medium fraction was enriched in these five minerals when compared to the coarse fraction. The Fe:Mn ratio in the fine fraction (29.8) and the total soil extract (29.4) were the same, possibly indicating trace amounts of soil present in the < 0.25 mm size fraction. Elemental recovery was > 90% for all except the < 0.25 mm fraction (74%), indicating the presence of another mineral element, possibly silicon, the second most abundant soil mineral at 30% by weight (Sposito, 1989).

Experiment-I

The 2-way interaction of temperature x moisture was significant for C mineralization (Table 3). But the ANOVA indicated that incubation temperature exerted a greater control on C mineralization over time than did soil moisture. The sum of squares between temperature levels was 15 times or higher than the sum of squares between moisture contents (Table 3). Temperature effects on total CO_2-C evolved during the experiment from soil only, and soil + crop residue are displayed in Fig. 1. Total levels of C for soil only and soil + crop residue were 10,100 and 11,900 µg C g^{-1}, respectively. More C mineralized from a SOM pool at the 32 °C incubation temperature than the combined SOM and residue C mineralized at 11 °C. Soil moisture also affected C mineralized (Fig. 2). Each increase in soil moisture was correlated with an increase in C mineralization from SOM and/or crop residue. But no negative effects were observed, as each increase in soil moisture increased the total mineral C evolved. Research indicates the upper limit of soil moisture for microbial respiration is 60% water filled pore space (WFPS), above which microbial respiration is reduced, due to limitations imposed by oxygen diffusion (Linn and Doran 1984). Torbert and Wood (1992) also observed highest microbial respiration at 60% WFPS over a bulk density range of 1.40–1.80 Mg m^{-3}. In our experiment, the high rate of moisture (0.28 g H_2O g^{-1} soil) occupied about 40% WFPS, thus avoiding oxygen diffusion limits.

The ANOVA were conducted on soil only or soil + crop residue separately because of the anticipated distance between the two treatments and the effect the difference would exert on the sample variance. Mineralized C was lowest at the 11 °C temperature, independent of soil moisture content and C source of either SOM or crop residue (Table 4). However, each step-wise increase in soil temperature (from 11 to 23, from 23 to 32 °C) significantly increased the total C mineralized from soil, or from soil + residue. Across temperatures, the range of C mineralized from soil was 161–880 µg C g^{-1} soil, and from soil + residue was 499–1643 µg C g^{-1} soil. Increased soil moisture also resulted in higher C mineralized, but the response was muted, when compared to the temperature effect, with a range 399–579 ug C g^{-1} soil and 1009–1310 µg C g^{-1} soil, respectively. A temperature gradient (5, 20, 35 °C) applied to soil collected from pineapple (*Ananas comosus*) plantations in Tahiti also resulted in higher C mineralized, by 95 and 47%, when compared to 5 °C, respectively (Waldrop and Firestone 2004). Analysis of the $\delta^{13}C$ signature of the CO_2 collected revealed that as temperature, but not soil moisture, increases, the soil microorganisms utilize older, recalcitrant

Table 3 ANOVA results for soil C mineralization during the laboratory experiments as affected by temperature, soil moisture, and crop residue particle size

	Effect	*DF*	*DF*	*F*-ratio	Pr > *F*
Experiment-I					
Soil C mineralized	Temperature (*T*)	2	24	972	< 0.0001
	Moisture (*M*)	2	24	61.7	< 0.0001
	$T \times M$	4	24	11.1	< 0.0001
Soil and residue C mineralized	Temperature (*T*)	2	24	223	< 0.0001
	Moisture (*M*)	2	24	14.9	< 0.0001
	$T \times M$	4	24	3.22	0.0277
Experiment-II					
Soil and residue C mineralized	Particle size (*P*)	1	23	271	< 0.0001
	Moisture (*M*)	3	23	16.7	0.0005
	$P \times M$	3	23	6.47	0.0025

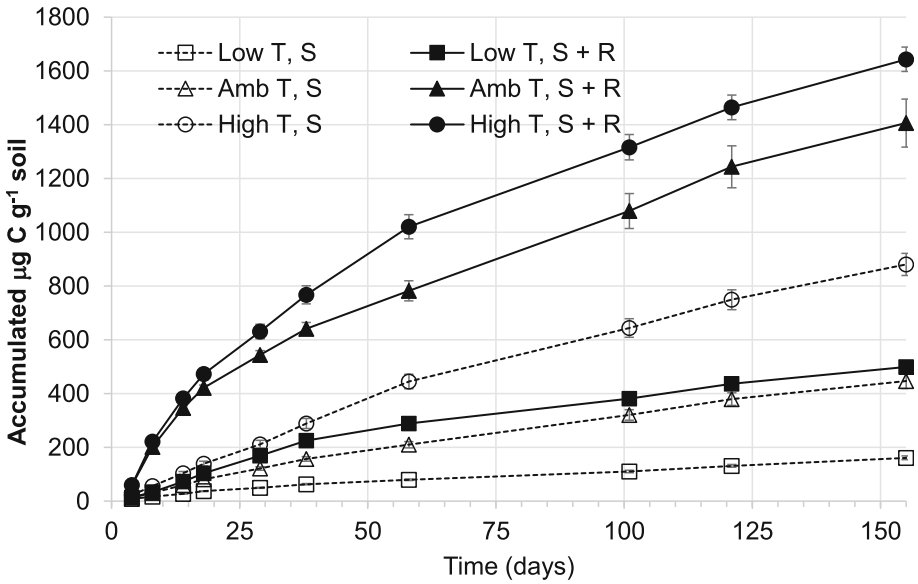

Fig. 1 Temperature effect on mineralized C evolved during Experiment-I from soil (S) only (open symbols) and soil amended with crop residue (S + R) (closed symbols). Means are across soil moisture levels. Vertical error bars represent ± 1 standard error of the mean

SOM as a substrate as well as more labile C substrates. Curtin et al. (2012) observed that both higher temperature (5–25 °C) and moisture (0.16–0.41 g H_2O g^{-1} soil) resulted in increases of C and N mineralized from SOM in pasture, arable, and vegetable soils. A different way to say this is that soil respiration declines as soil moisture declines, and the effect is larger at warmer soil temperatures. Zak et al. (1999) reasoned that substrate diffusion limits metabolically active soil microorganisms at warm temperatures and that the limitation is lower at cooler soil temperatures because physiological activity and substrate demand drop at cooler soil temperature (5 °C). These studies provide evidence that substrate pool size, not necessarily reaction kinetics, is temperature dependent in soils.

The initial soil C concentration was 10,100 µg g^{-1}, which would mean that 1.6, 4.5, and 8.8% of the soil C was mineralized in treatments without crop residue (Table 4). These low values reflect the intense tillage practices used on sugarcane soils in south Louisiana that keep labile soil C pools depleted, with respect to total SOC. In the Pacific Northwest, all tillage reduced SOC, but more intense tillage using a moldboard plow depleted microbial and physically protected SOC pools, such as particulate organic matter, when compared to disk and chisel plow, or no-till, which were considered less intensive (Awale et al. 2017). Any SOC remaining exhibits a higher degree of recalcitrance, or resistance to decomposition, over time. Each temperature increase resulted in greater accumulated CO_2-C over the course of the experiment. But the absolute differences between the soil only and matching soil + residue samples were not consistent between temperature levels. The soil samples evolved 32% the C evolved by the

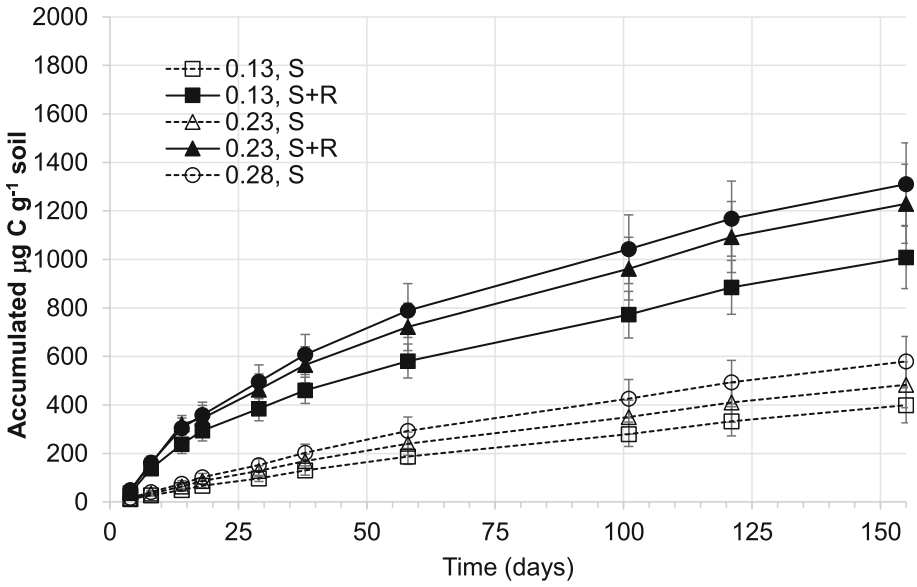

Fig. 2 Soil moisture affect (0.13, 0.23, and 0.28 g H_2O g^{-1} soil) on mineralized C during Experiment-I from soil (S) only (open symbols) and soil amended with crop residue (S + R) (closed symbols). Means are across temperature treatments. Vertical error bars represent ± 1 standard error of the mean

Table 4 Total C mineralized (CO_2-C g^{-1} soil) during Experiment-I as affected by temperature and soil moisture in soil alone (top) or soil with crop residue (middle), or as affected by residue particle size and soil moisture (bottom)

Incubation temperature	Soil moisture content (g H_2O g^{-1} soil)			Mean
	0.13	0.23	0.28	
11 °C	139 g[a]	165 g	180 g	161 Z
23 °C	344 f	447 e	551 d	447 Y
32 °C	713 c	921 b	1007 a	880 X
Mean	339 C	510 B	579 A	

	0.13	0.23	0.28	
11 °C	460 d	489 d	549 d	499 Z
23 °C	1094 c	1559 b	1565 b	1406 Y
32 °C	1472 b	1641 ab	1816 a	1643 X
Mean	1009 B	1230 A	1310 A	

Particle size			
	0.17	0.23	
Control	226 e	225 e	225 Z
>2.0 mm	654 c	819 a	736 X
0.25–2.0 mm	748 b	767 ab	758 X
<0.25 mm	505 d	559 d	532 Y
Mean	533 B	593 A	

[a]2-way interaction means followed by the same lowercase letter, and main effect means followed by the same uppercase letter, in the same sub-table, are not different at the $P < 0.05$ level

soil + residue samples for 11 and 23 °C, but 53% for the samples incubated at 32 °C (Fig. 1, Table 4).

The rate of C mineralization varied greatly between soil samples with residue additions at the initial portion of the experiment, 4–18 days, more than at any other time over the 155 days (Fig. 3). Soil amended with crop residue evolved more CO_2 at 23 and 32 °C, than at 11 °C, with an accumulated amount of C liberated by 18 days equal to 470 and 420 µg C g^{-1} soil, or 47 and 42% of the initial residue C added (990 µg C g^{-1} soil). Over the same 18 days, the soil samples, not amended with crop residue, evolved just over 82 and 140 µg C g^{-1} soil. For the remainder of the experiment, soil C evolved at a more consistent rate across residue treatments, with averages for low, ambient, and

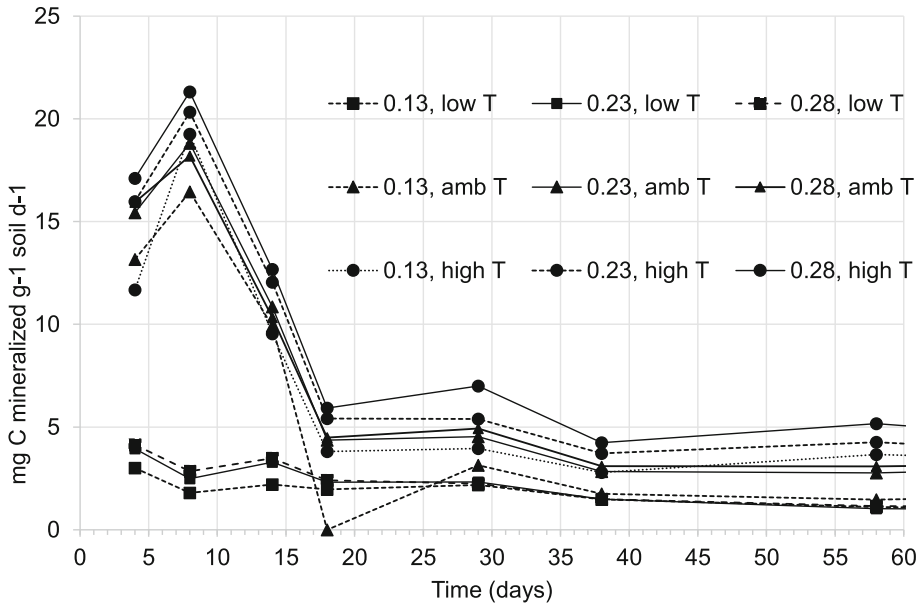

Fig. 3 The temperature × moisture interaction for C mineralization rates over the initial 18 d period from soil samples amended with sugarcane crop residue. Both 23 °C and 32 °C incubation temperatures caused a rapid rate of C mineralization that was not observed at the low (11 °C) temperature at any moisture content. Numbers reflect gravimetric moisture content (e.g., 0.13 g H_2O g^{-1} soil)

high temperatures of 0.79, 1.75, and 2.61 µg C g^{-1} soil day^{-1}. Q_{10} values were calculated using the observed increase in C mineralization rate between ambient and low, and ambient and high temperature treatments (Fig. 4). Q_{10} calculated for the soil C mineralization at each sample point were 1.5–3.5, for increases of 12 °C (low *T* to ambient *T*) and 9 °C (ambient *T* to high *T*); these were similar to what one would anticipate (Davidson and Janssens 2006). The Q_{10}'s for the high–ambient treatment were equal to 1.0–1.7 for the duration of the experiment. But the Q_{10} values were much higher (3–7.5) for the initial high rate of respiration produced when crop residue was added to soil at ambient temperatures, when compared to the lower respiratory response of the low temperature treatment.

First-order kinetics was used to estimate decomposition rate constants. Treatment differences between the samples with residue and the samples with soil only at each time point were used to estimate the % C remaining. Ideally, these two pools would represent microbial respiration of added plant residue-derived C and basil respiration of microbial biomass and SOC-derived CO_2, respectively (Kuzyakov 2006). But, it is not possible to exclude CO_2 contributions resulting from priming effects of added substrate on SOC pools or incubation treatment-altered SOC pool availability without using isotope analysis. The

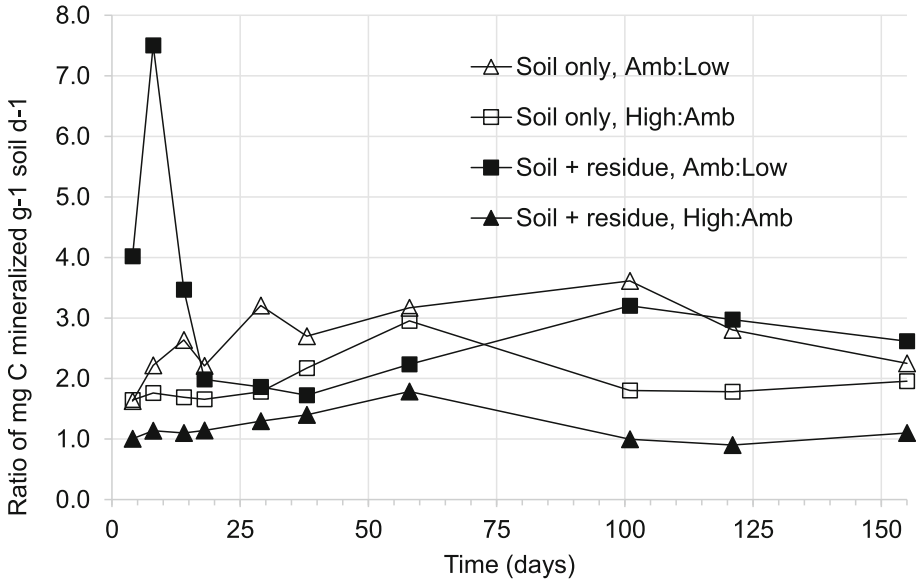

Fig. 4 The ratio of soil C mineralization rates between ambient (23 °C) and low (11 °C) and ambient (23 °C) and elevated (32 °C) with and without crop residue

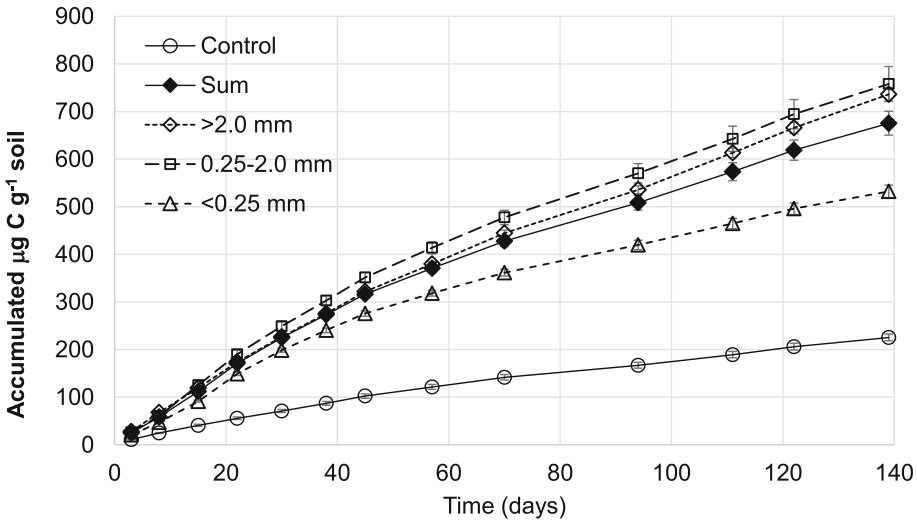

Fig. 5 Accumulated CO_2-C measured from the headspace of jars during the soil incubation. The solid symbol is the sum of > 2.0 mm, 0.25–2.0 mm, and < 0.25 mm size fractions. Means are across soil moisture levels. Vertical error bars represent ± 1 standard error of the mean

natural log of % remaining is plotted over time, and the equation is solved for the rate constant 'k' by:

$$\ln(Ct/C0)/t = -k \quad (1)$$

Regression lines were fit to the observed data using Excel. Using these first-order constants, the above equation can be solved for half-life by:

$$\ln(50/100)/k = t \quad (2)$$

where 't' is in days. The treatment main effect correlation coefficient (R^2) for each regression analysis was > 0.91 and the rate constants 'k' for 11, 23, and 32 °C, and 0.13, 0.23, and 0.28 g H_2O g^{-1} soil, were 0.003, 0.019, 0.008, 0.005, 0.007, and 0.008 day^{-1}, respectively. The calculated half-lives for the crop residue incubated under these conditions were 257, 35.7, 82.9, 129, 92.5, 87.4 days, respectively. Sugarcane post-harvest crop residue decomposed over a 338 days period at a similar rate of 0.0046 day^{-1} (Spain and Hodgen 1994). Field decomposition rates observed would likely be greater due to mechanical effects of tillage, wind, and rain. Examples for derived 'k' for field comparison include barley (*Hordeum vulgare* L.), 0.004 day^{-1}; oat (*Avena sativa* L.), 0.003 day^{-1}; spring wheat (*Triticum aestivum* L.), 0.037 day^{-1}; and winter wheat, 0.028 day^{-1} (Steiner et al. 1999); several decomposition models split rate constants into phases, such as a rapid (0.025 day^{-1}) and slow (0.0091 day^{-1}) decomposition rate, for the same crop residue source (Gilmour et al. 1998). More recently, Stewart et al. (2015) reported decomposition rate constants dependent on plant chemistry, including lignin content, varied by crop residue source and the soil's previous cropping history, with an average range of 0.088–0.101 and 0.0037–0.0044 day^{-1}, respectively, for active and passive pools of residue C. And others have tied residue decomposition to plant chemistry using solid-state ^{13}C nuclear magnetic resonance spectroscopy (Wang et al. 2004). The range in literature values suggests empirically derived rate constants are specific to cropping system and are impacted by experimental protocol. But the similar methodology used to derive the rate constants is a good indication of a consensus involving crop residue decomposition kinetics.

Experiment-II

The practice of shredding sugarcane residue after harvest, to speed its decomposition, is becoming more common and growers attest to its effectiveness (Mr. Ted Broussard, 2015, personal communication). For 2013–2016, the average low air temperatures were 11, 10, 5.1, and 7.4 °C for November, December, January, and February, respectively. The experiment was conducted in a cold room at 10 °C to approximate the cooler winter temperatures typically observed in the sugarcane growing area of south Louisiana. The 2-way interaction of particle size and soil moisture was significant for C mineralization (Table 3). The ANOVA also indicated that incubation particle size exerted a greater control on accumulated C mineralized than did soil moisture. The sum of squares between particle sizes was 16 times higher than the sum of squares between moisture contents (Table 3). As the experiment progressed, the C evolved from soil for the largest size fractions (> 2.0 mm and 0.25–2.0 mm) was clearly greater than for the smallest size fraction (< 0.25 mm) (Fig. 5). After 139 days, the total CO_2-C accumulated exhibited this difference, where > 2.0 and 0.25–2.0 mm fractions evolved on average 747 µg C, which was ~ 40% greater than the < 0.25 mm size fraction (532 µg C) and 230% greater than the control (225 µg C) (Table 4). However, when data are presented on a % remaining basis by subtracting the CO_2-C evolved from the no-residue control, the > 2.0, 0.25–2.0, and < 0.25 mm particle size fractions evolved

61, 72, and 91% of the residue C added, respectively (Table 4). By this account, shredding the residue into progressively smaller pieces may have merit as a practice to speed residue decomposition.

The effect of particle size on decomposition is not consistent in other reported research. Pea (*Pisum sativum*) residue of 10-mm particle size initially decomposed faster, when compared to a 1-mm particle size, but after 90 days the residue decomposition was identical (Jensen 1994). However, the pea residue exhibited a C:N ratio of 21:1, common to legumes, that should not require an external N source for decomposition. A further study with barley residue, ≤ 3 versus 25 mm, generated information that over the short-term net residue, N mineralization was higher for smaller particle sizes of possibly due to a more intimate residue–soil–microorganism contact (Ambus and Jensen, 1997). But, over the long term, mineralization was similar across particle size. Similar findings were made by Angers and Recous (1997). They incubated wheat and green rye (*Secale cerale*) residues 0.06–10-mm in diameter and found that while initially smaller pieces of residue resulted in increased CO_2 evolved after adding them to soil, over time the larger pieces produced similar accumulated CO_2 results. However, they concluded that physical protection of crop residue fragments (equivalent to POM) was dependent on particle size and that rapid decomposition occurs when nutrients, substrates, and soil solution are in close proximity.

In our experiments, the C:N ratio of the sugarcane residue was > 75:1. However, in the particle size experiment, C mineralized readily from residue with a C:N ratio of 81 (0.25–2.0 mm) or 159 (> 2.0 mm) was the same (Table 4). This contrasts with Gilmour et al. (1998) who found that as residue C:N increases, decomposition decreases. The > 2.0-mm residue added 1213 and 7.625 µg of total C and N g^{-1} soil, respectively, to a soil containing 10,100, 890, and 10 µg of total C, total N, and inorganic N g^{-1} soil. The soil and residue "microcosm" C:N ratio would still be 13:1. This could explain why the high C:N ratio of sugarcane residue decomposed rapidly. However, the 10 µg inorganic N g^{-1} soil cannot be overlooked as a prime candidate for the rapid mineralization of sugarcane crop residue exhibiting high C:N ratios.

Kennedy and Arceneaux (2006) burned, swept residue into wheel furrows, incorporated residue in soil (0–7 cm) using a disk cultivator, shredded the residue using a commercial chipper shredder, and left this shredded residue on the soil surface or incorporated it into the soil. Their results indicated shredding and incorporating residue increased soil respiration (40 kg C ha^{-1} day^{-1}), relative to other treatments (25 kg C ha^{-1} day^{-1}). A trash blanket of 5 Mg residue ha^{-1} consisting of 400 kg C Mg^{-1} residue would be equivalent to 2.0 Mg C ha^{-1}. Using the first-order rate constant derived in Experiment-I (0.0083 day^{-1}), the C should be liberated at a rate of $\sim$ 17 kg ha^{-1} day^{-1}, which is comparable to the rate those researchers observed.

Significant differences were observed because of the moisture content used in the incubation. But soil moisture again was of secondary importance in terms of decomposition variance observed. However, moisture could be a secondary effect given the fact that the range of soil moisture was between 0.17 and 0.23 g H_2O g^{-1} soil. Research has demonstrated that aerobic microbial processes occur optimally at 60% wfps; however, the soil water activity remains at 99% even as soils dry past the permanent wilting point (− 1.5 MPa) (Harris 1981). Given the range at which soil microorganisms thrive, subsets (e.g., heterotrophic, nitrifiers, bacteria, fungi) likely make use of available substrates in all but the most extreme soil conditions.

Conclusions

Green-cane harvesting of sugarcane deposits large amounts of crop residue on the soil surface every year. Our results indicate that sugarcane crop residue decomposes readily in soils $\geq$ 23 °C at a rate > 0.008 day^{-1}. For the initial 2 w, crop residue decomposition proceeded at its highest rate for 23 °C and 28 °C temperatures. The observed decomposition rate was the lowest at the 11 °C temperature. Residue decomposition was not impeded at any soil moisture evaluated (0.13–0.28 g H_2O g^{-1} soil) to any great degree. But, generally, the higher soil moisture, the faster the decomposition rate. In this study, as cane residue particle size decreased, the decomposition increased. The smallest fraction (< 0.25 mm) decomposed > 90% during the 139 days experiment. Overall, increasing the days between harvest and onset of cool temperatures (e.g., 11 °C) will allow crop residue to decompose more completely and recycle organic matter and nutrients. By recycling crop residue into soils, as opposed to burning the residue, early harvested fields may see improvements in SOM and nutrient levels over time.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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